X-ray binary observations by GRAVITY and GRAVITY+ perspectives

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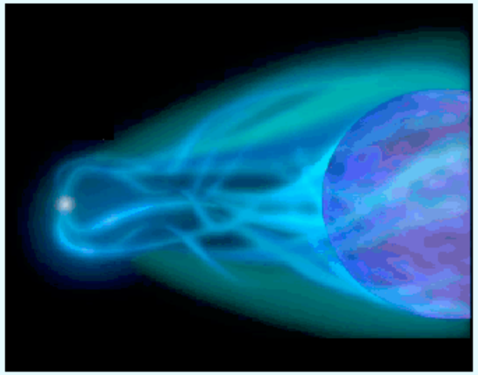
Outline

- A few generalities on X-ray binaries (XrB)

- GRAVITY observations of XrB
  ➡ The microquasar SS 433
  ➡ The supergiant High Mass X-ray binaries: Bp Cru

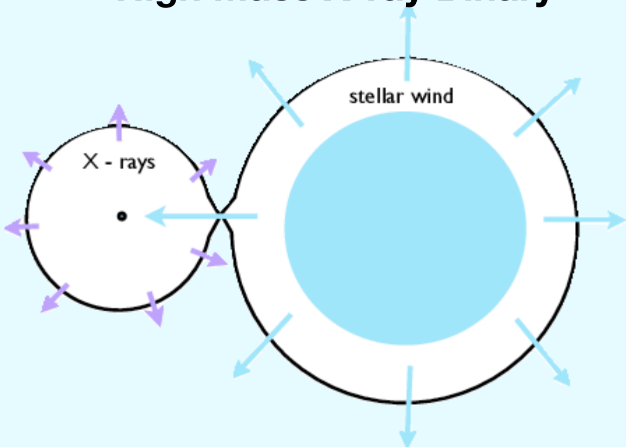
- Perspectives GRAVITY+
  ➡number of targets
  ➡orbital constraints of binary systems
  ➡accretion-ejection processes during outburst

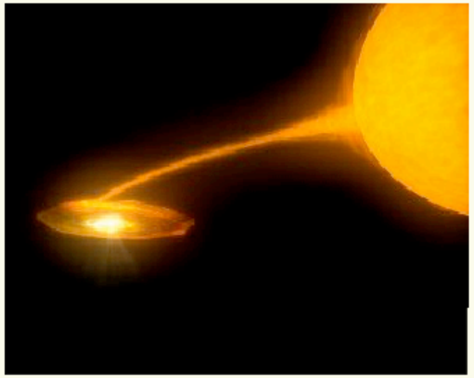
X-ray Binaries



HMXB

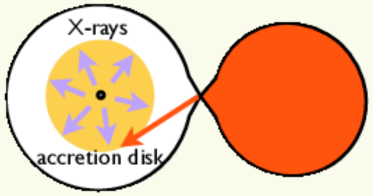
High Mass X-ray Binary





LMXB

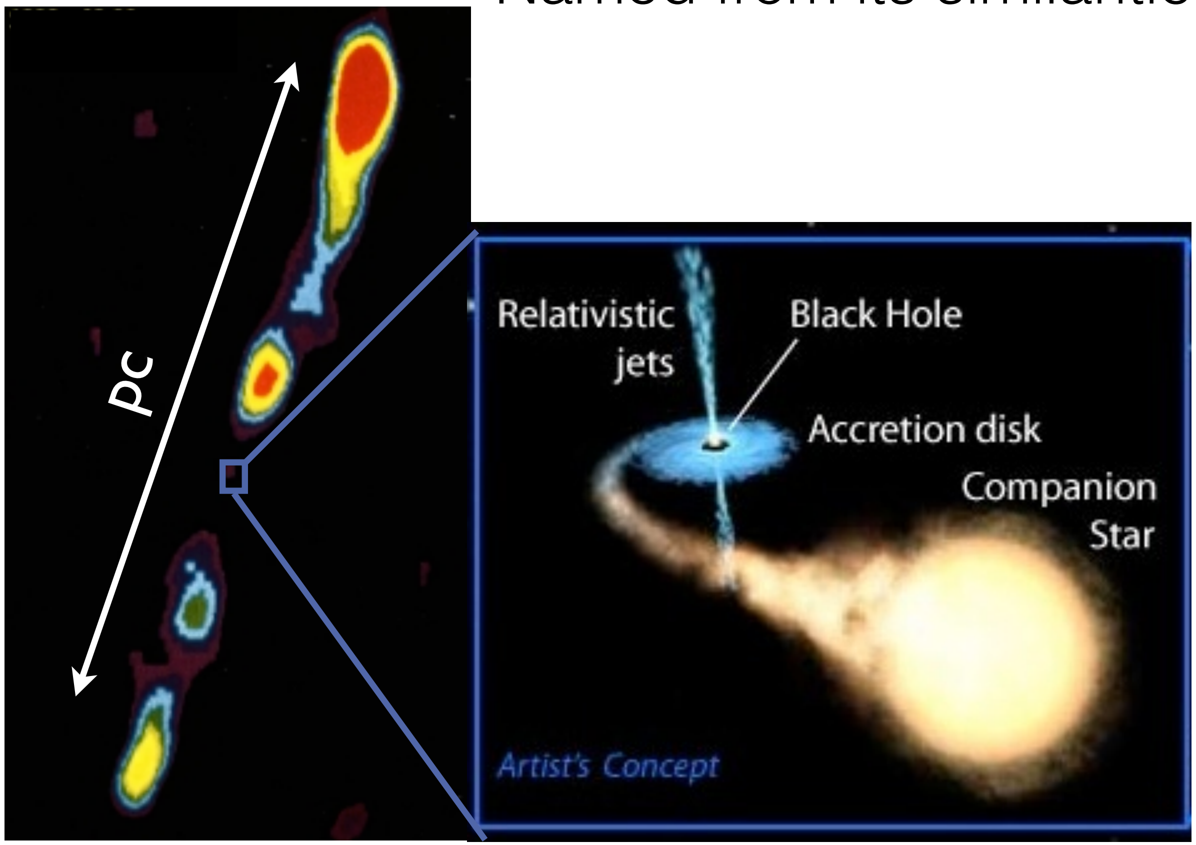
Low Mass X-ray Binary

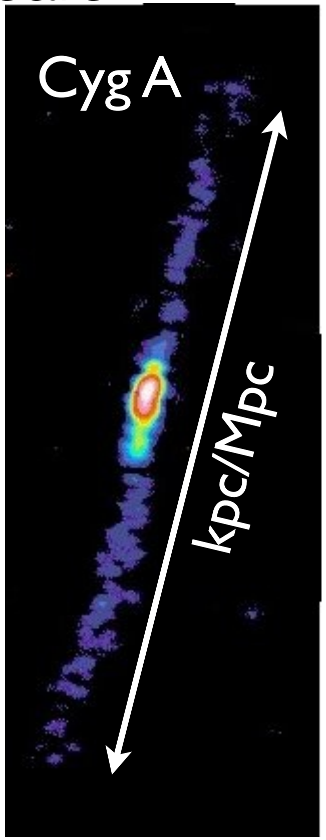


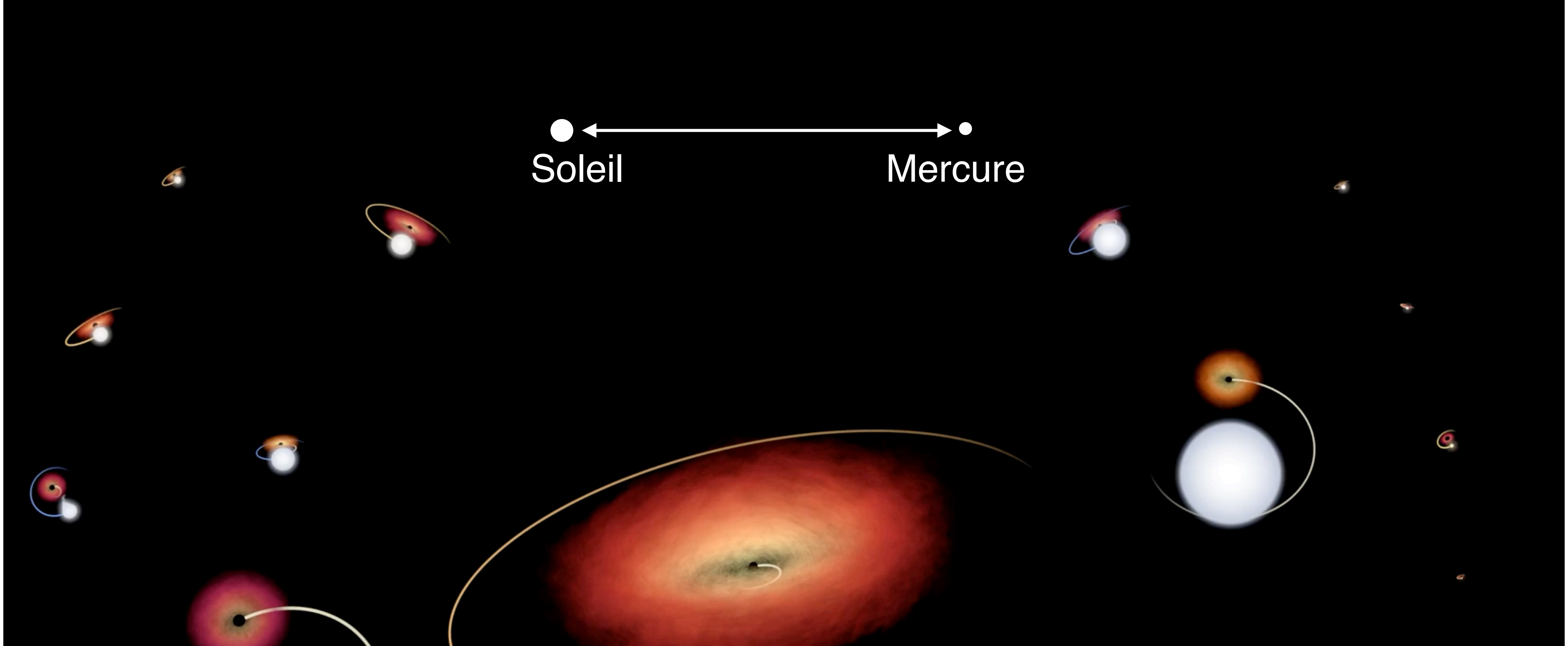
Microquasar = XrB with Jet

In 1992 the first microquasar was detected: a double-sided **radio jet** from the compact source 1E1740.7–2942 in the Galactic Centre (Mirabel et al. 1992)

Named from its similarities with quasars







- Semi-major axis a < 1mas i.e. below the imaging resolution even of the largest optical/ near-infrared interferometers.
- Spectral differential interferometry can provide direct spatial information on scales as small as ~ 1–10 µas but requires a bright enough object for fringe tracking
- Nearly all LMXBs and the great majority of HMXBs cannot be observed interferometrically with the current facilities.

➡Vela X-1 (Choquet+14) with VLTI/AMBER and VLTI/PIONIER

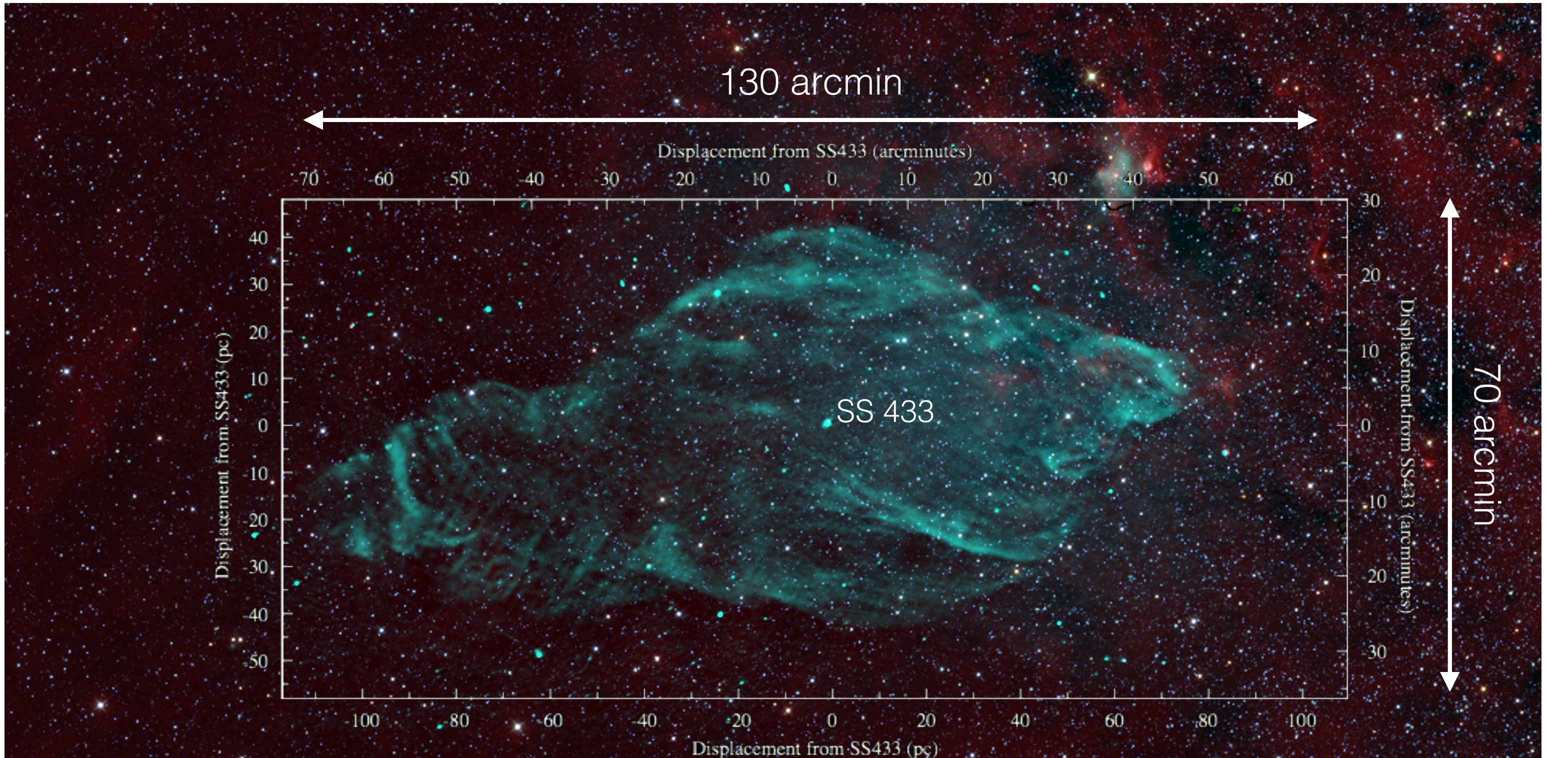
➡CI Cam (Thureau+09) with PTI and IOTA

https://www.youtube.com/watch?v=-IBmERQ7L30

The Microquasar
SS 433

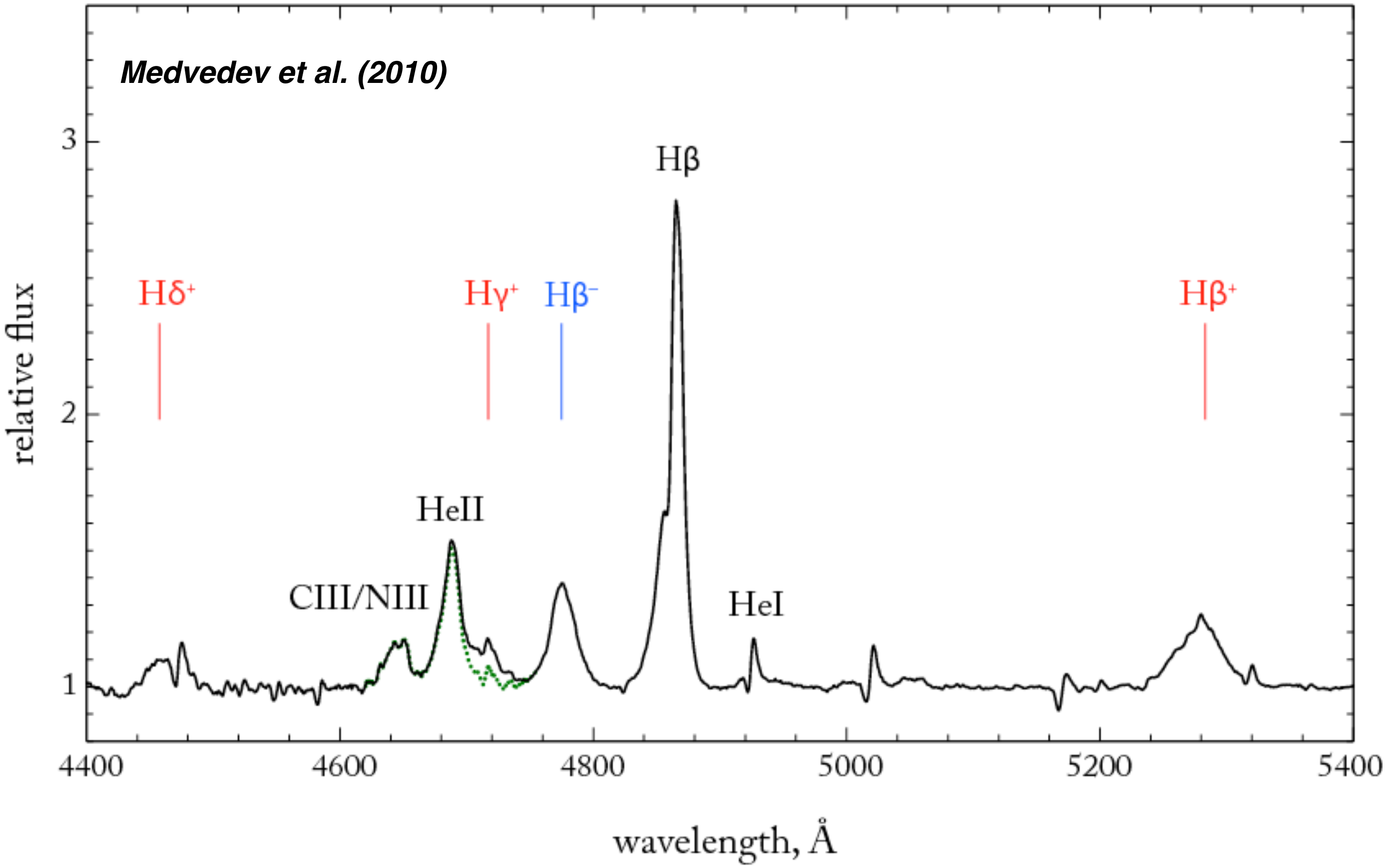
What is SS 433?

- Discovered in the 70's. In the galactic plane. K=8.1!
- Eclipsing binary with Period of 13.6 days, the primary may be a ~10 M
- At a distance of 5.5 kpc, embedded in the radio nebula W50



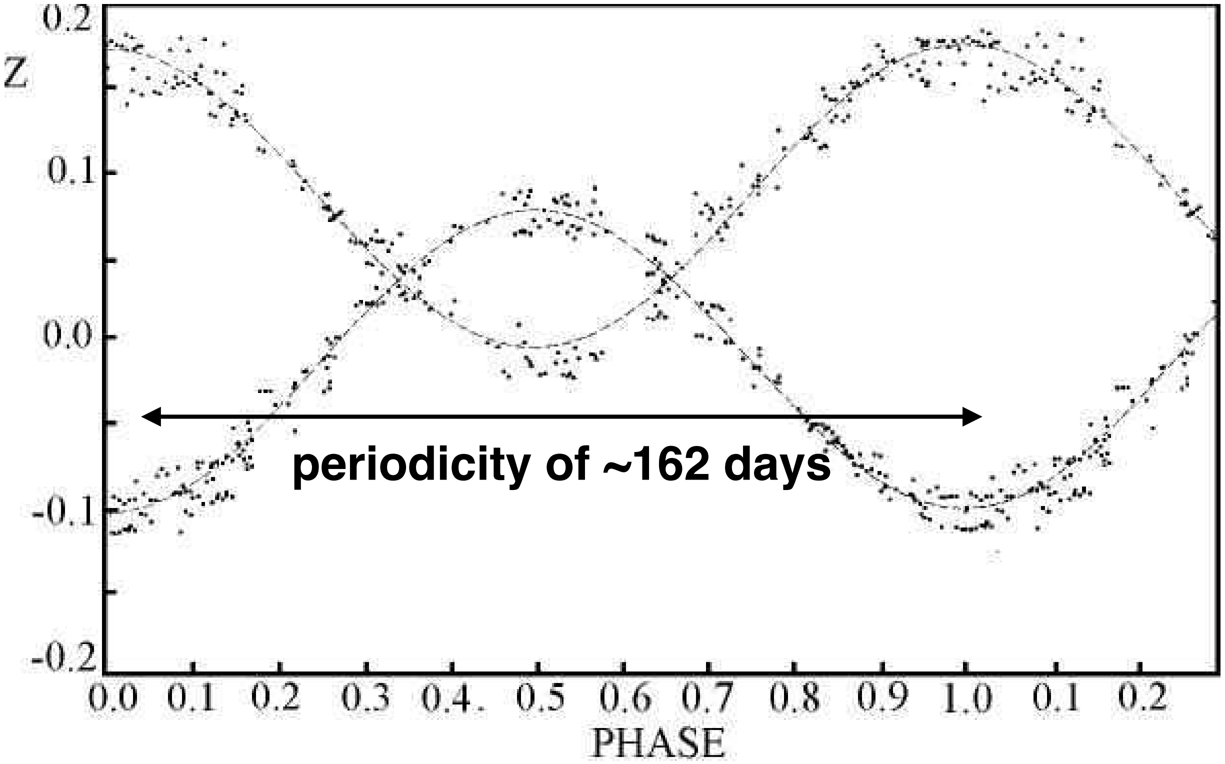
W50 supernova remnant in radio (green) against the infrared background of stars and dust (red).

Rest and Moving Lines



- Optical/IR spectrum:
  - Broad emission lines (**rest lines**)
  - Doppler (blue and red) shifted lines (**moving lines**)

Moving Lines: Jet Signatures

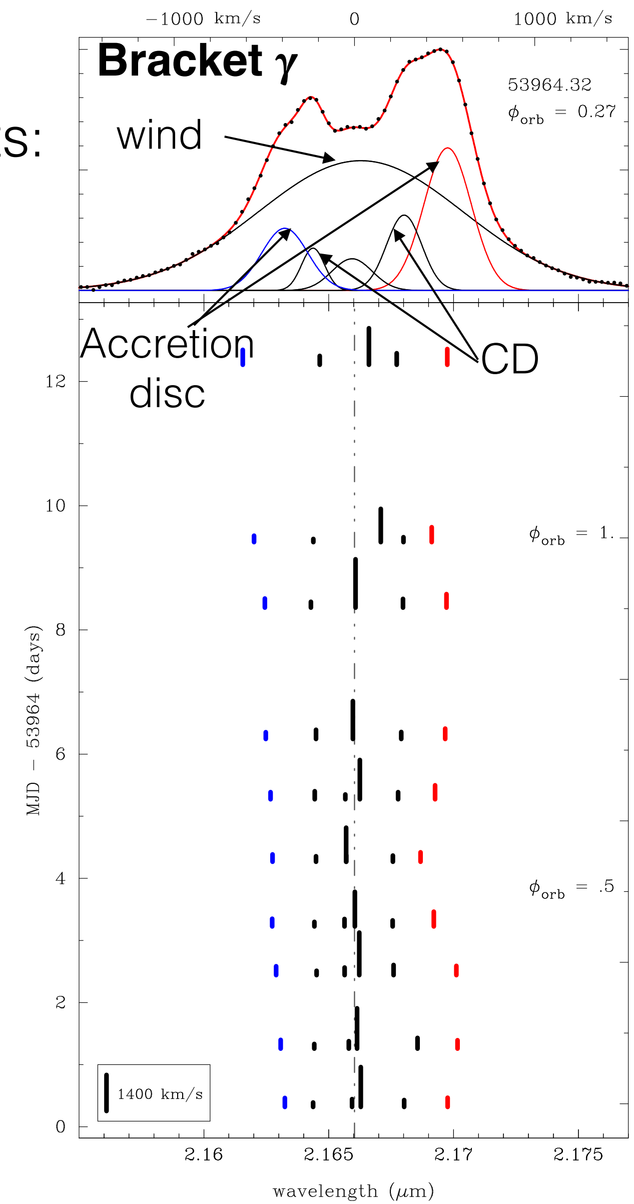


- Rapidly interpreted as signature of collimated, oppositely ejected jet (v~0.26c) precessing (162 days) and nutating (6.5 days)
- Variable, periodic, Doppler shifts reaching ~50000 km/s in redshift and ~30000 km/s in blueshift

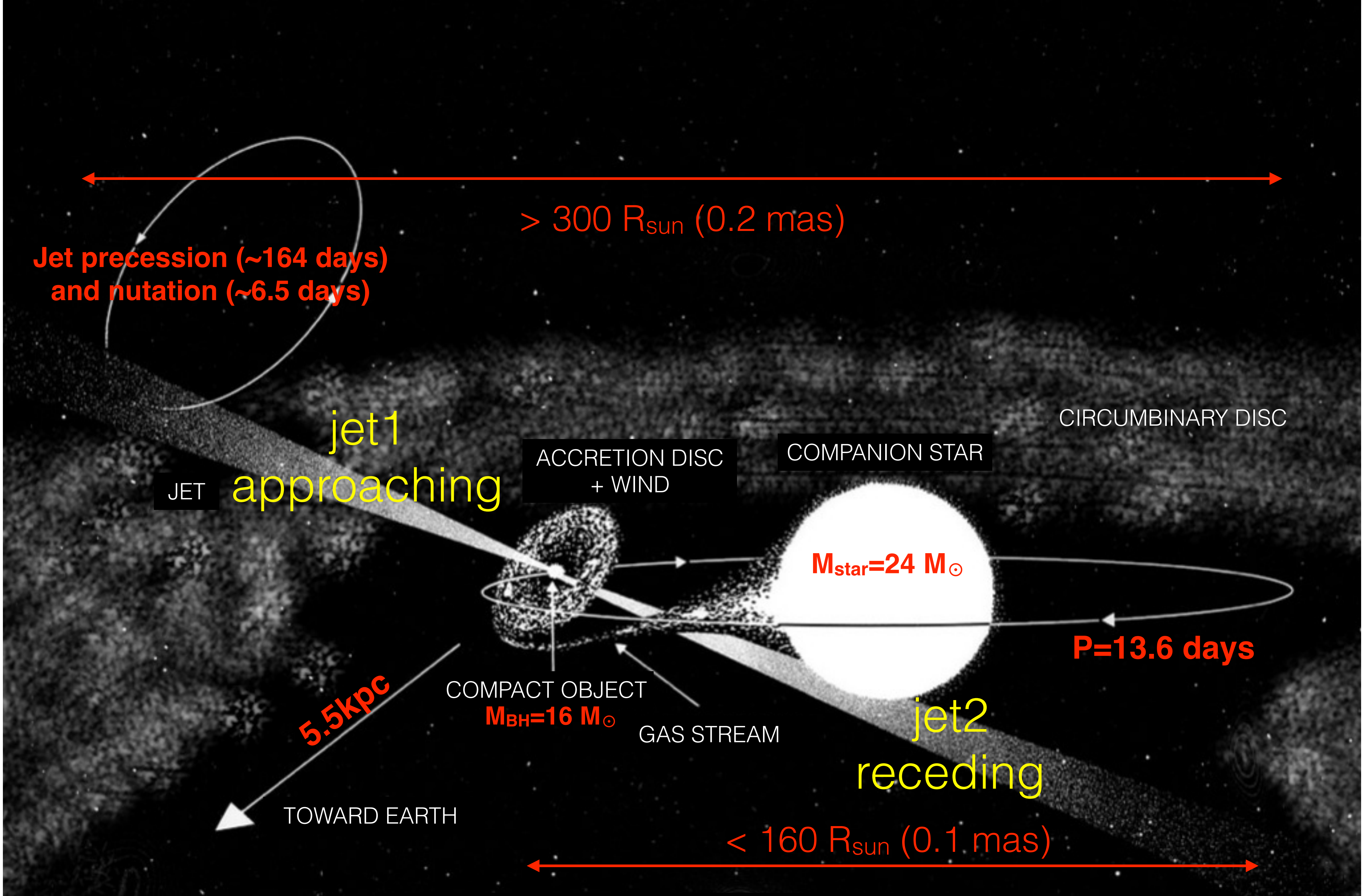
Stationnary lines
Wind, accretion and Circumbinary discs

Stationary lines generally consist of different components:

- A broad component is identified as emitted in that **wind from the accretion disc.**
- Two narrow remarkably constant components, one permanently redshifted and the other permanently to the blue signature of a **circumbinary ring** (the inner rim of an excretion disc?)
- Some « extra » broadening can be due to the presence of two narrow components at comparatively extreme excursions in velocity signature. Signature of a ring or **disc orbiting the compact object itself.**



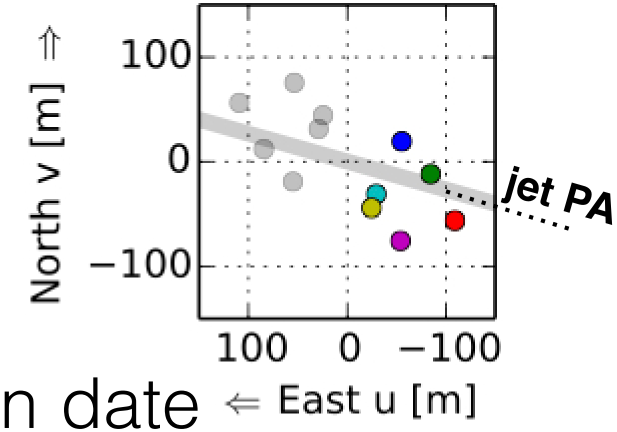
Perez & Blundell (2009)

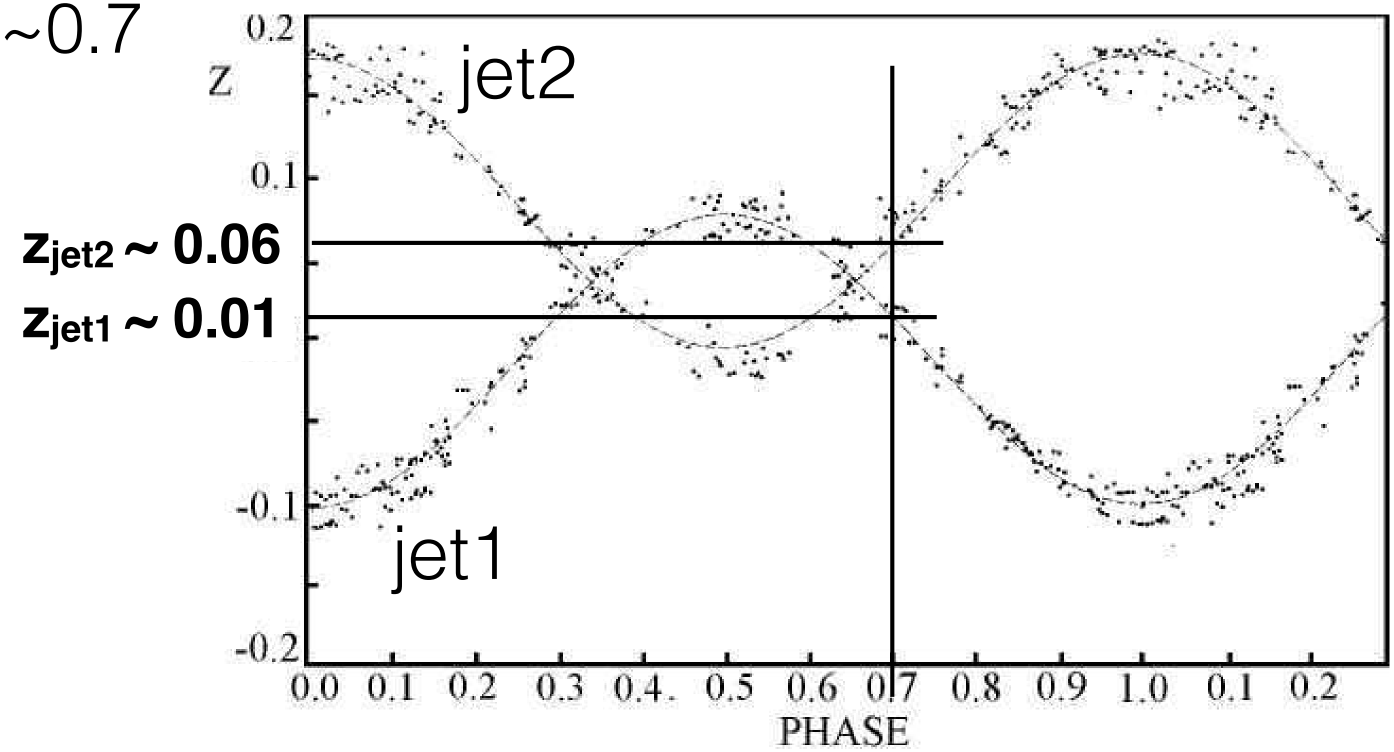


The SS-433 System

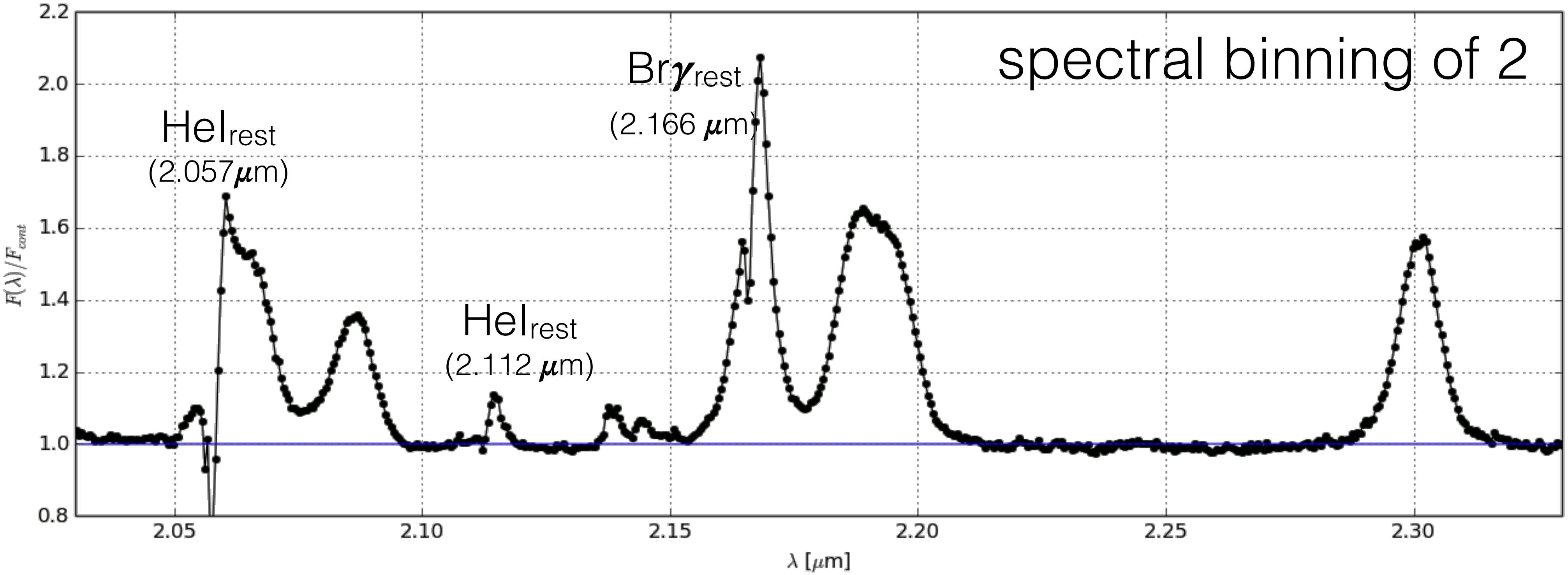
Observation with GRAVITY

- 3.5h with the 4 UTs, the 16th July 2016
- uv-plane (coincidentally) aligned with the jet PA
- The jet precession phase at the observation date is ~0.7





The GRAVITY Spectrum

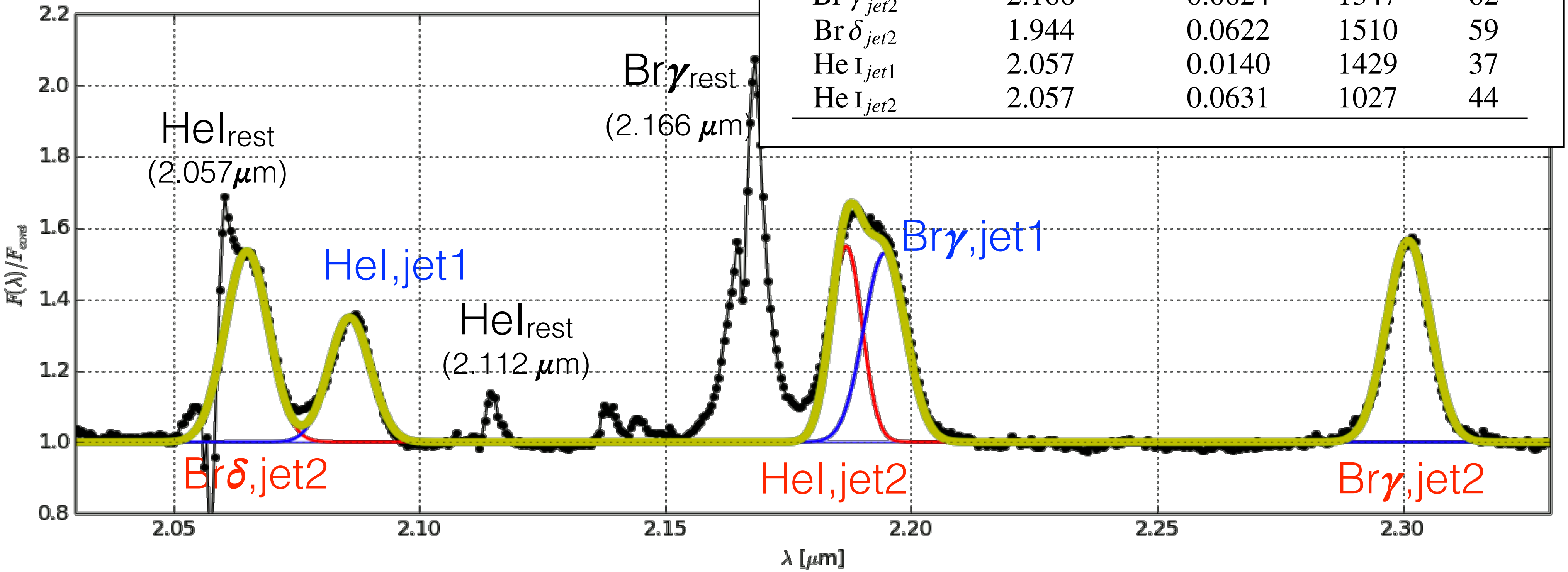


<u>Stationary lines</u>

- Brγ is double-peaked
- HeI with P Cygni profile

The GRAVIT

Name	Rest wavelength (μm)	redshift	FWHM (km s^{-1})	EW (Å)
Br γ_{jet1}	2.166	0.0132	1364	56
Br γ_{jet2}	2.166	0.0624	1347	62
Br δ_{jet2}	1.944	0.0622	1510	59
He I $_{jet1}$	2.057	0.0140	1429	37
He I $_{jet2}$	2.057	0.0631	1027	44



<u>Jet lines</u>

- Emission features agree with the jet line shifts expected at the observation date
- Brγ, HeI from jet1 and jet2 and Brδ from jet1

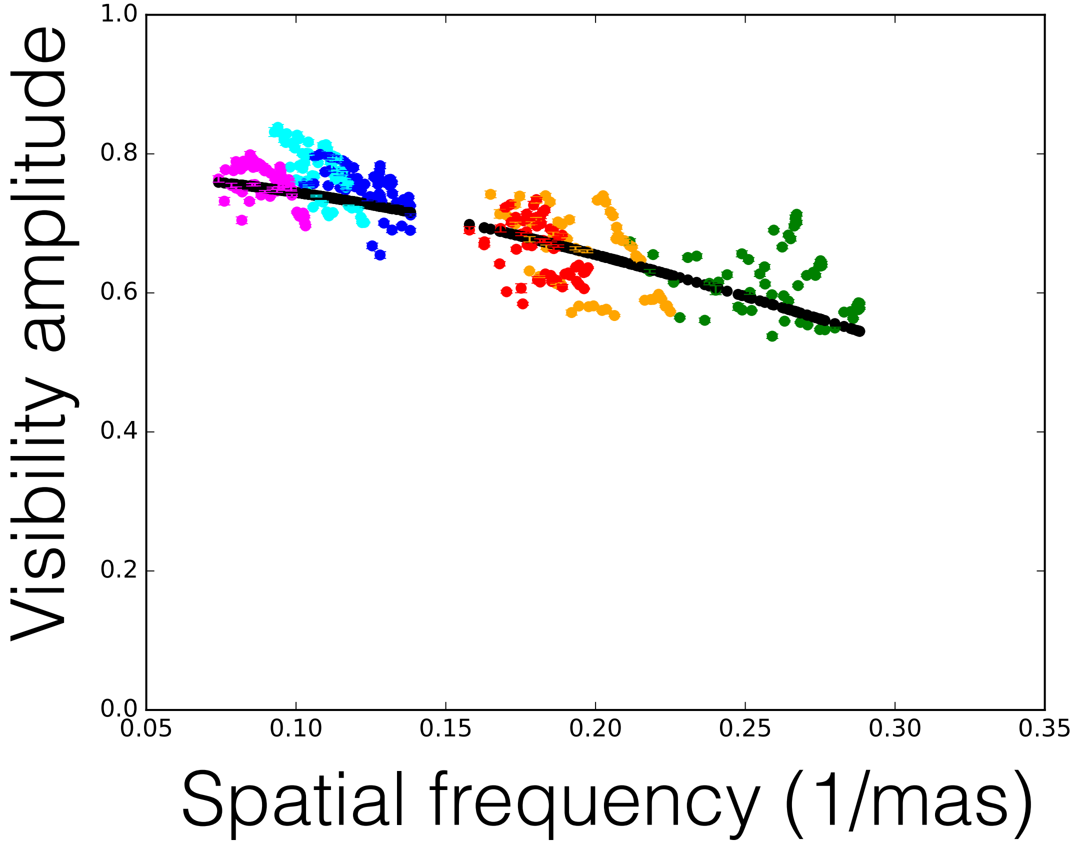
Interferometric observables

Continuum Visibility

- Systematic drop versus baseline length

- No closure phase measurable

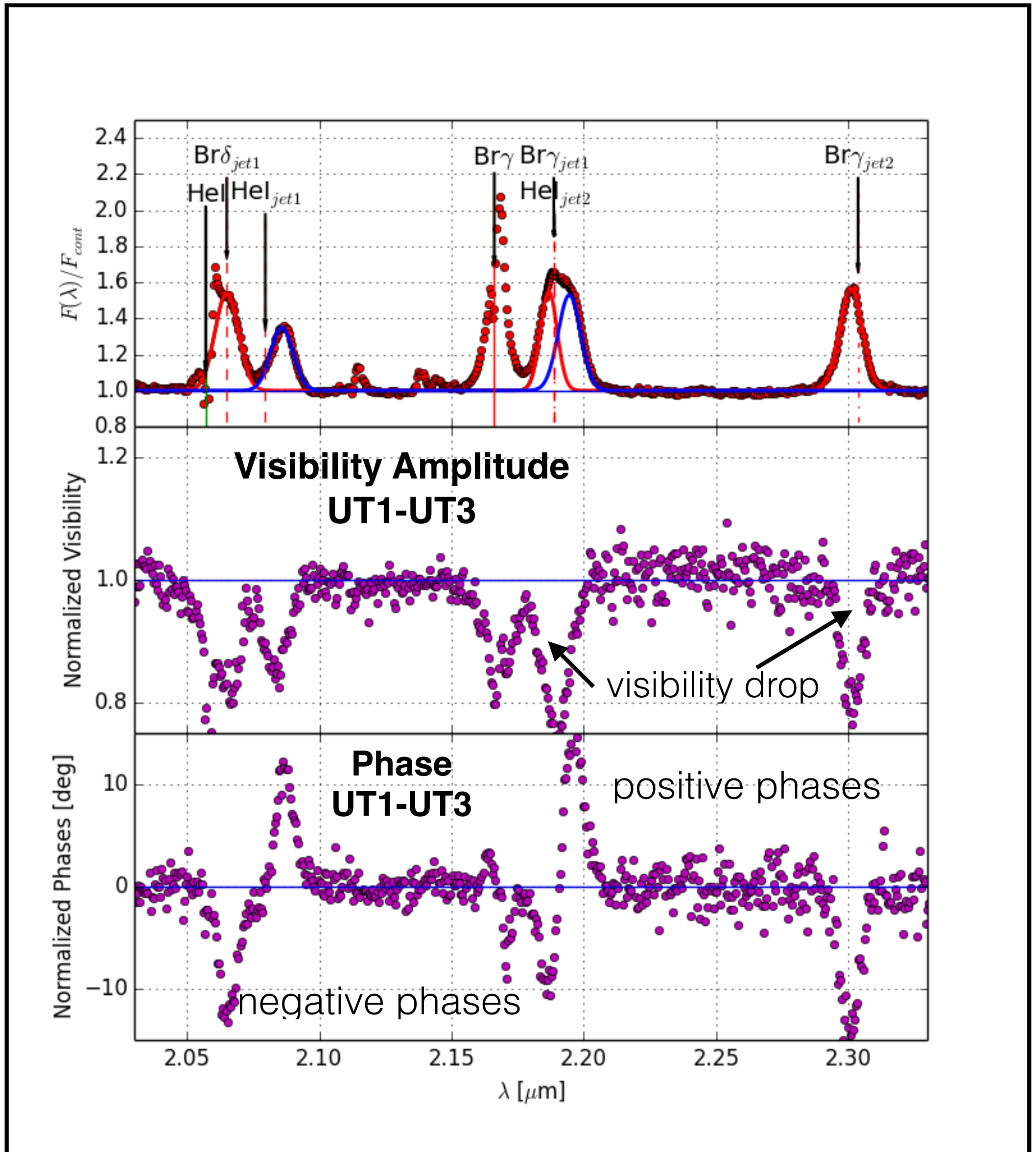
- Simple modeling with a Gaussian disk:



  - 90% from emitting region of 0.8mas
  - 10% from diffuse background (>15mas)

Interferometric observables

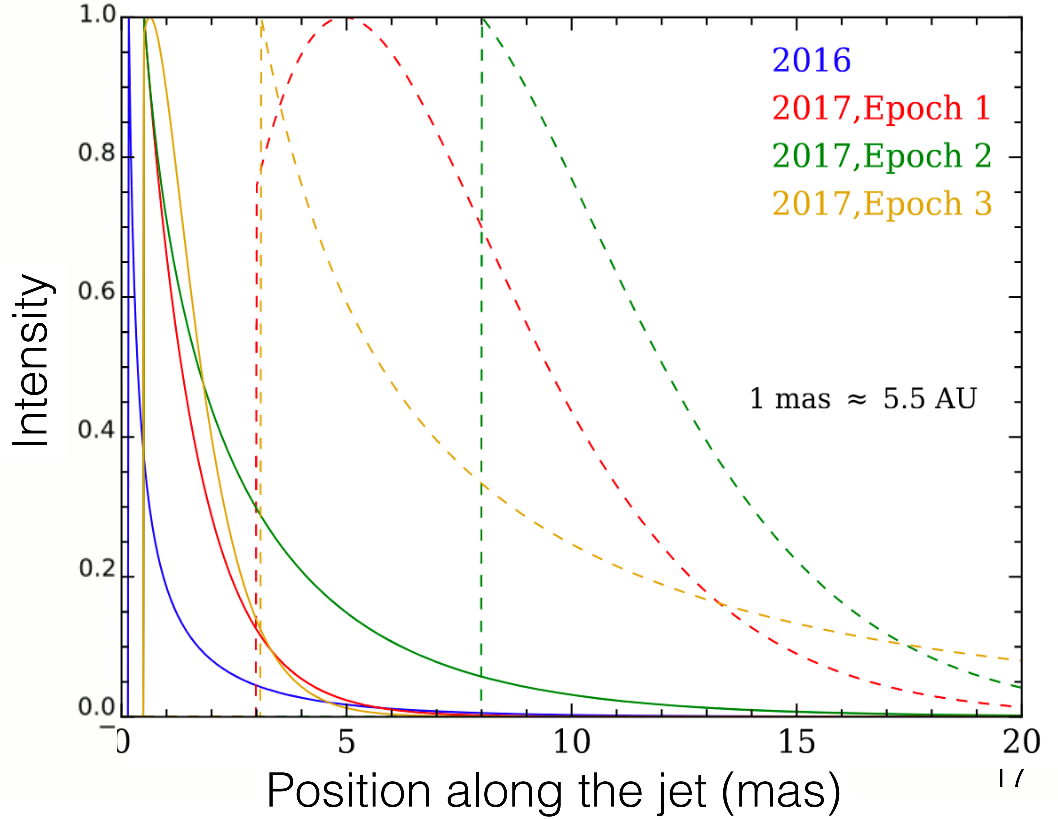
Lines visibilities and (differential) phases



Jet line Model

Method: fit all jet lines (flux, vis. amplitude and phase) together assuming the same jet intensity profile moving at 0.26c

- An exponentially decreasing intensity profile preferred to a gaussian one ($\Delta\chi^2 > 36$ for 57 dof)

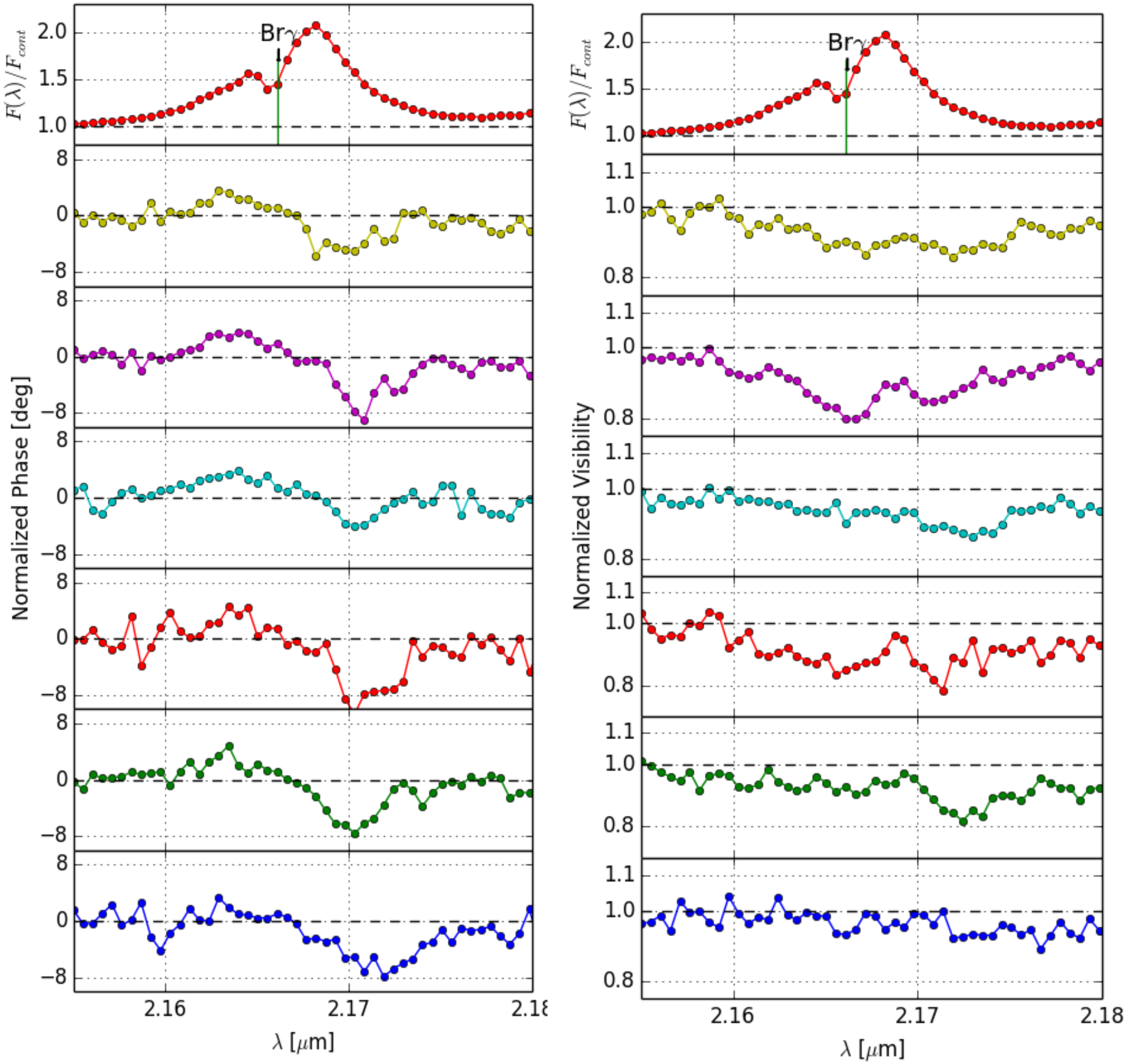


- Best fit with:
  - PA=75°±20° (3σ error)
  - s=1.7±0.6 mas,
  - a=-0.15±0.34 mas

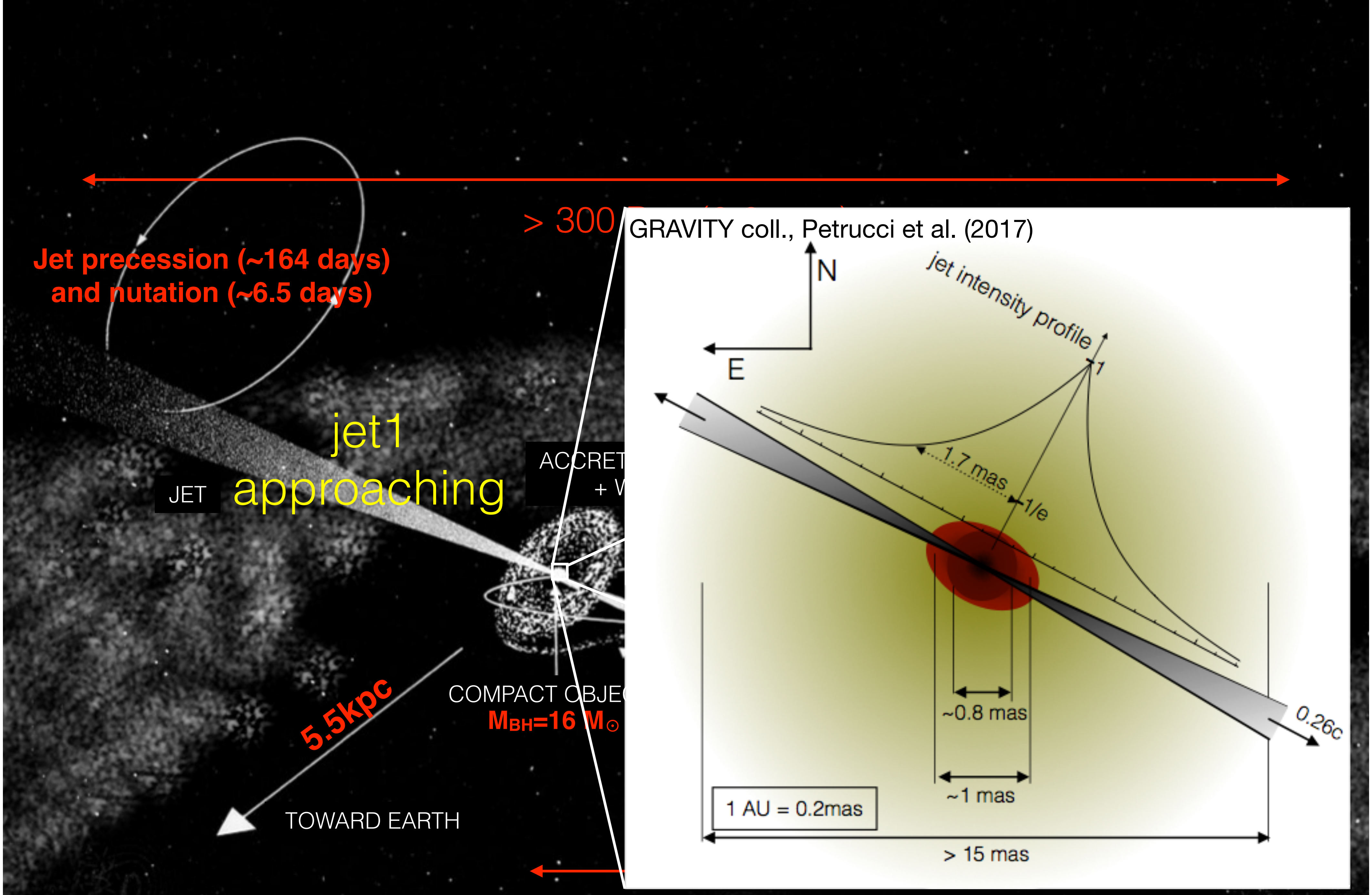
- Transverse size < 1.2 mas

- See also Waisberg+19 for the detection of multiple bullets in the jet

Stationary line: Brγ

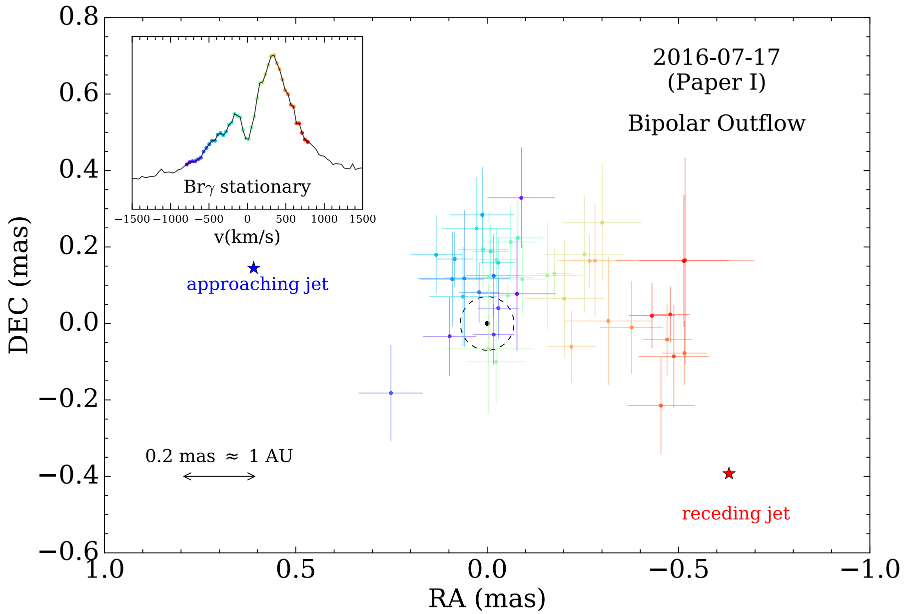


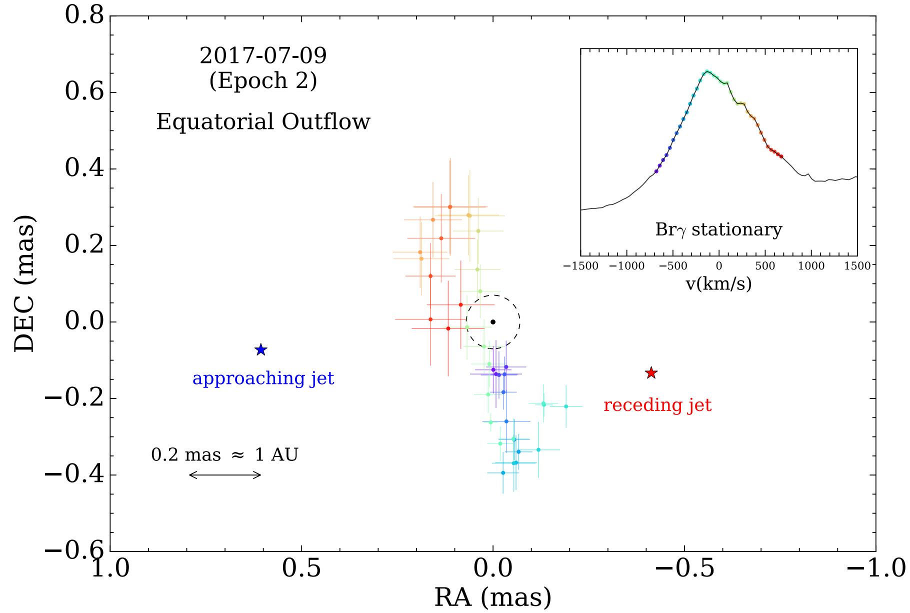
- Visibilities clearly drop across the line for all the baselines
- Deeper for longer baselines.
- Emitting region size is found to be ~1 mas
- Phases behavior suggest East-West oriented geometry, i.e., in a direction similar to the jet one



The SS-433 System

Variable Accretion-Ejection Structure





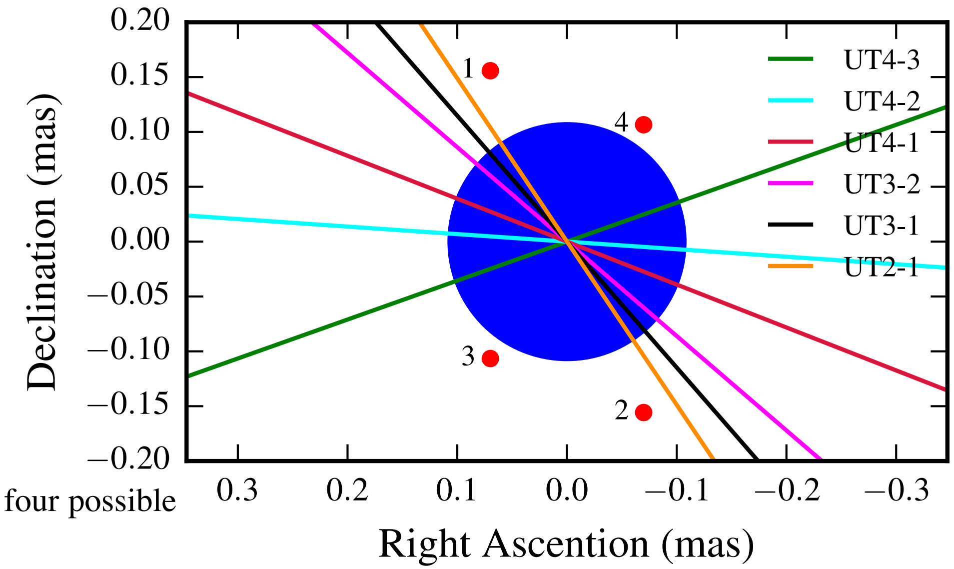
- The stationary emission line of Brγ changed from a bipolar-dominated to an equatorial-dominated outflow for observations spaced by one year
- GRAVITY campaign this year (5 obs separated by a few weeks): more to come

The supergiant High Mass X-ray binaries: Bp Cru

BP Cru

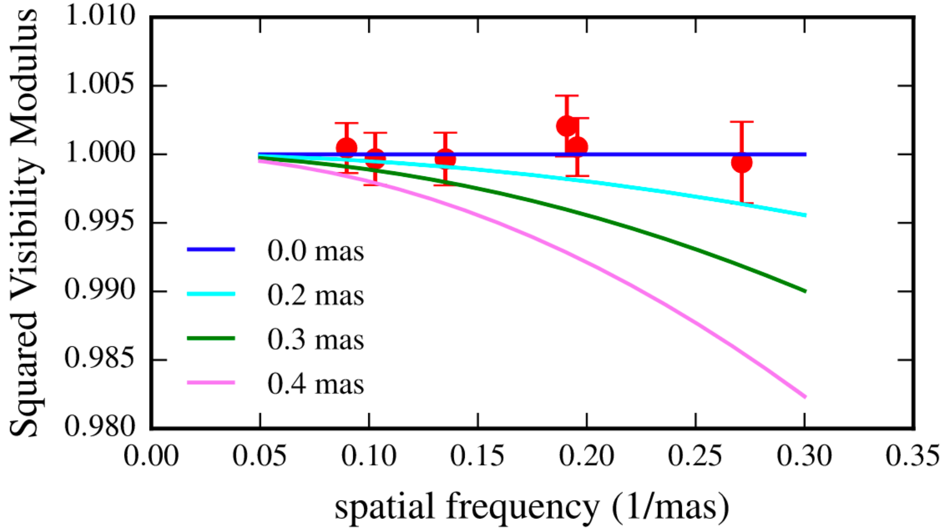
- Among the brightest HMXBs in the K band (K = 5.7) and the most eccentric orbit (e=0.46)
- Binary system of a pulsar GX 301-2 embedded in the dense stellar wind of the hypergiant Wray 977
- No precise astrometric information on the binary system (inclination, ascending node) -> the exact position of the pulsar on the sky plane is not known.
- Observed with GRAVITY in 2016

Waisberg et al. (2017), ApJ, 844, 72

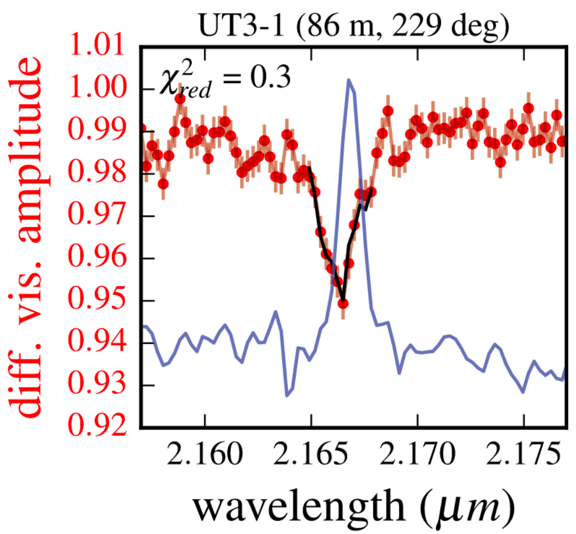


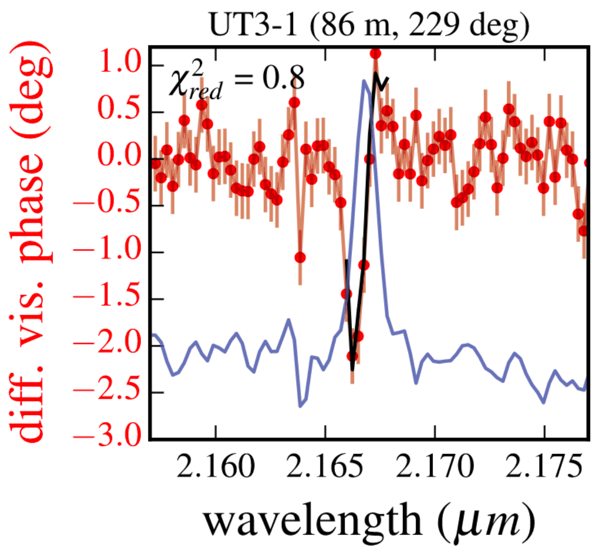
Donor star (photospheric radius ~70$R_{\odot}$) and the predicted four possible positions of the pulsar (red)

GRAVITY results



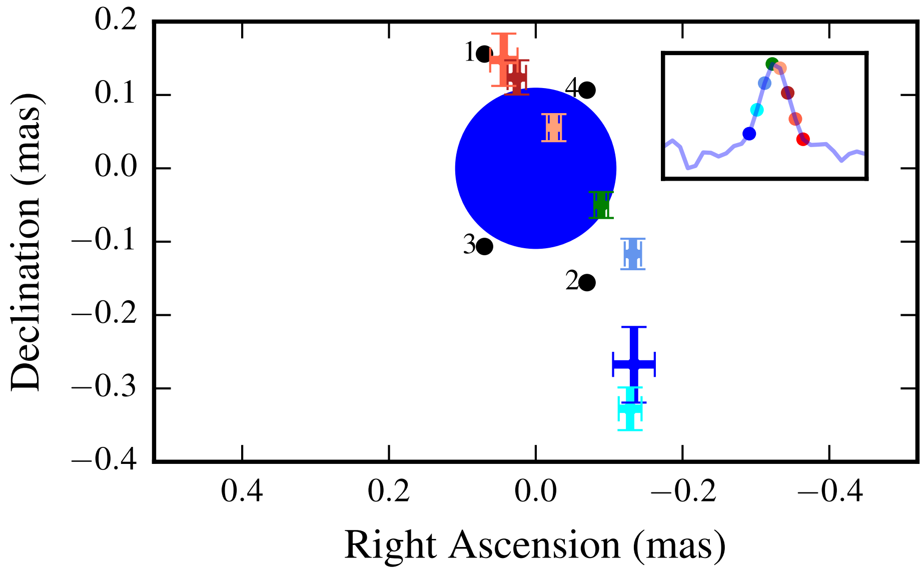
The data are most consistent with an unresolved continuum of size 0.2 mas dominated by the supergiant photosphere

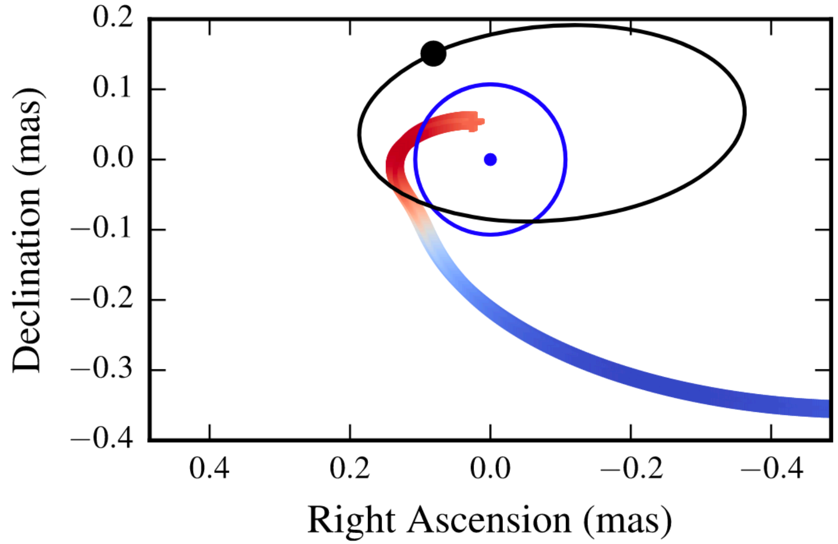




Clear visibility and phase drops across the Brγ line profile

GRAVITY results



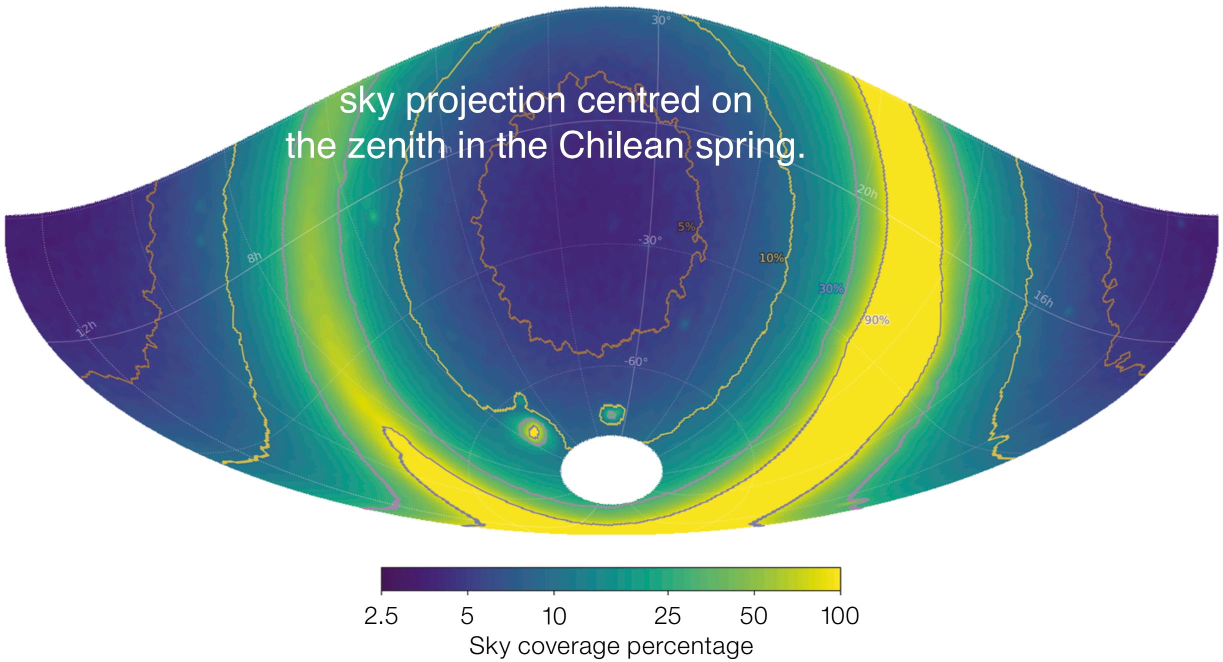


Spherical wind from the star + a tidal stream of gas of enhanced density that trails the compact object along its orbit

Perspectives with GRAVITY+

Gravity+

- With a 4-5 magnitudes improvement, a limit magnitude for fringe tracker K_{lim}=13 and separation of 30 arcsec



➡ severals tens LMXB and HMXB (compared to a few HMXB with Gravity)

➡ completely new field

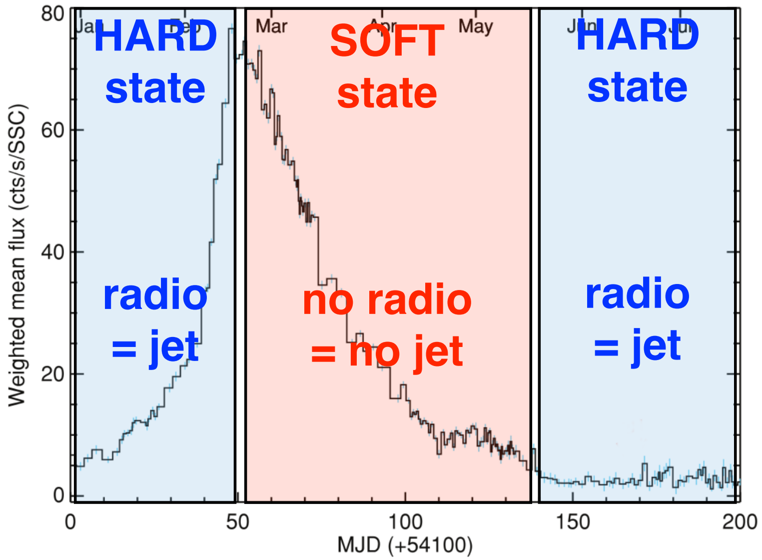
✓Galactic LMXB Catalogue (Avakyan+, 2023): 25 with K < 18 (K~16 in outburst, and GRS 1915+105 with K~12)

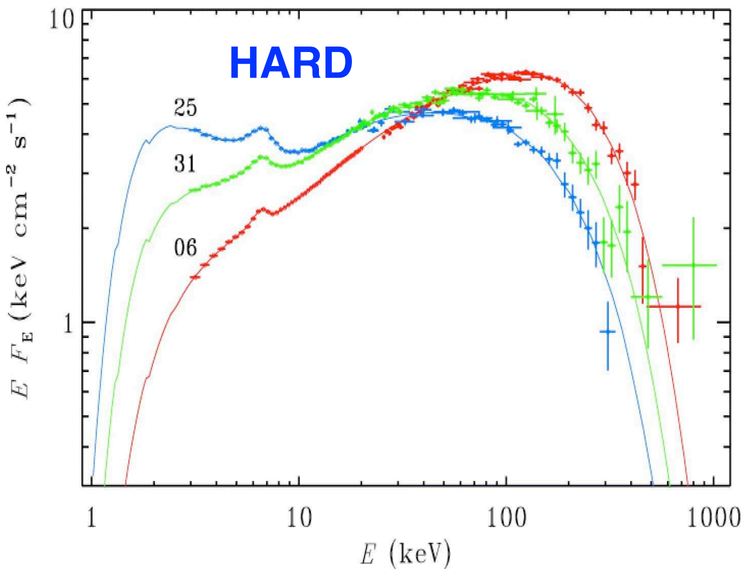
✓Galactic HMXB catalogue (Neumann+, 2023): 75 with K < 13

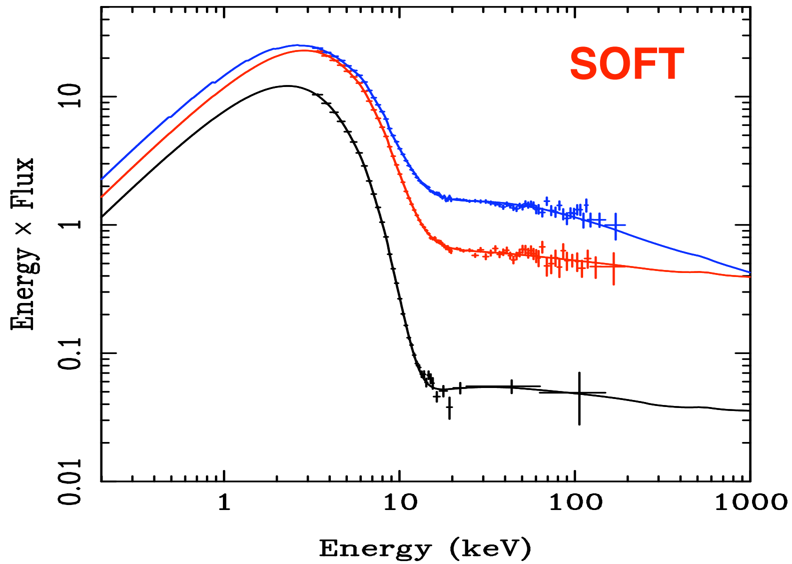
Constraining the Binary parameters

- Orbital mouvement of a star around a BH or NS to better determine:
  - the inclination of the system (important input for e.g. X-ray modelling)
  - the compact object mass:
    - ➡ BH vs NS
    - ➡ helping to constrain the NS equation of state
    - ➡ …

X-ray binaries in outburst

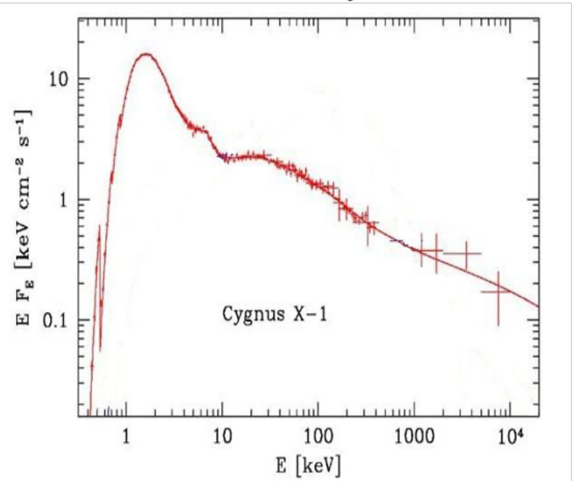


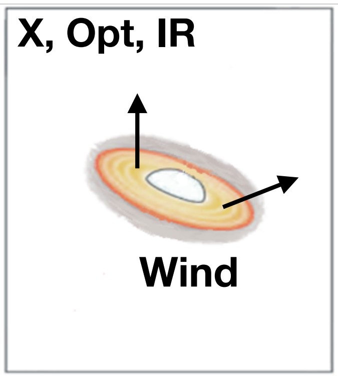


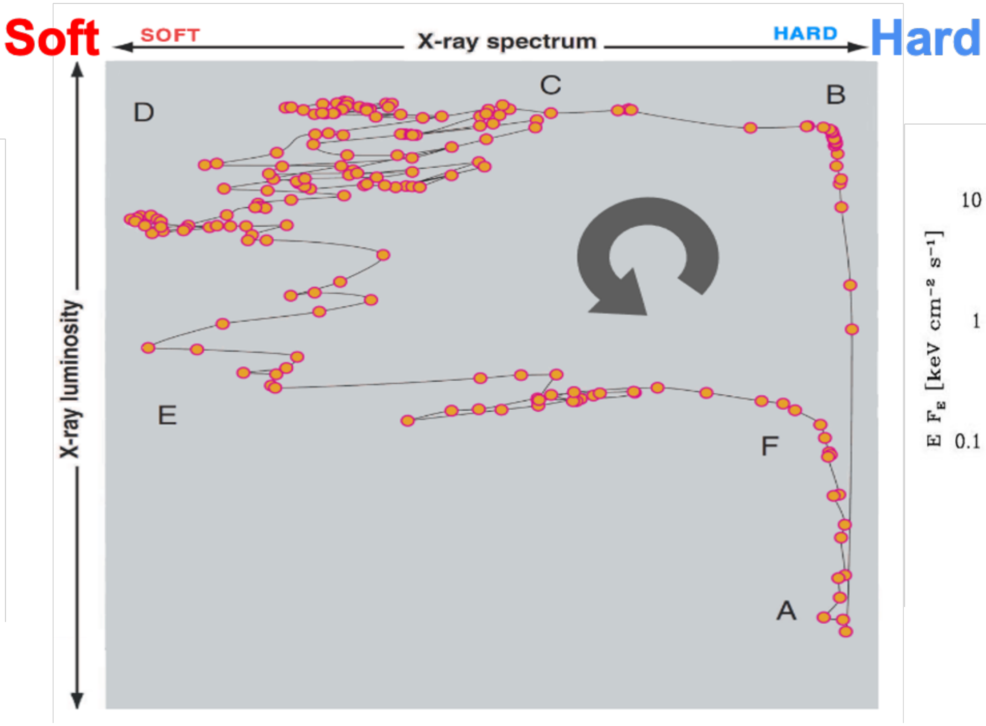


X-ray binaries in outburst

Dominated by disk

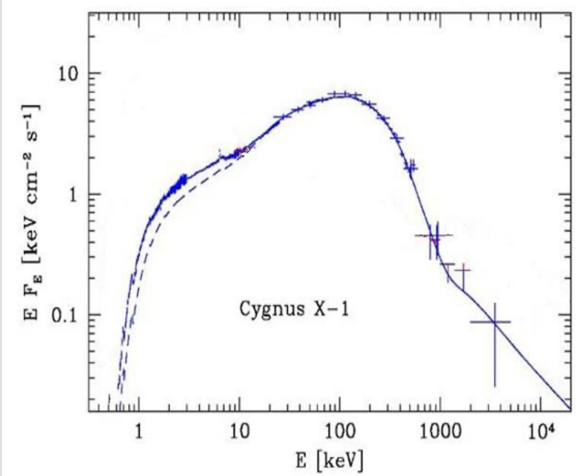


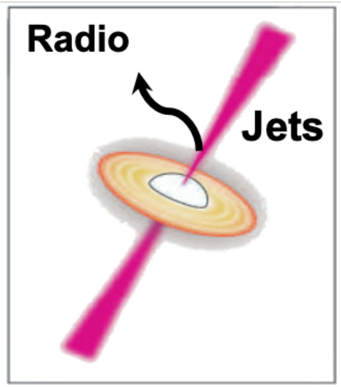




- ToO mode generally required
- broad band coverage helpful

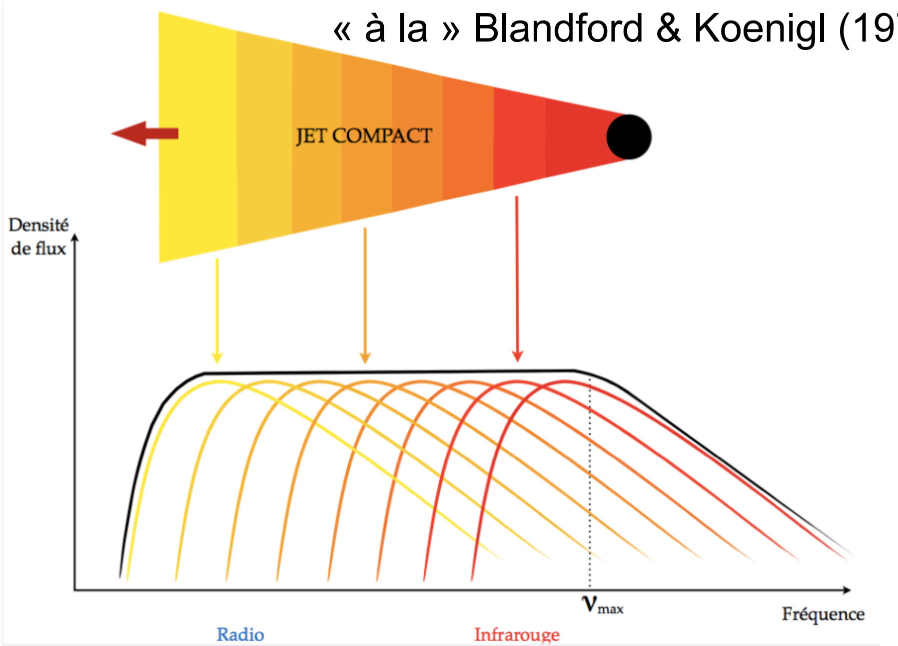
Dominated by corona





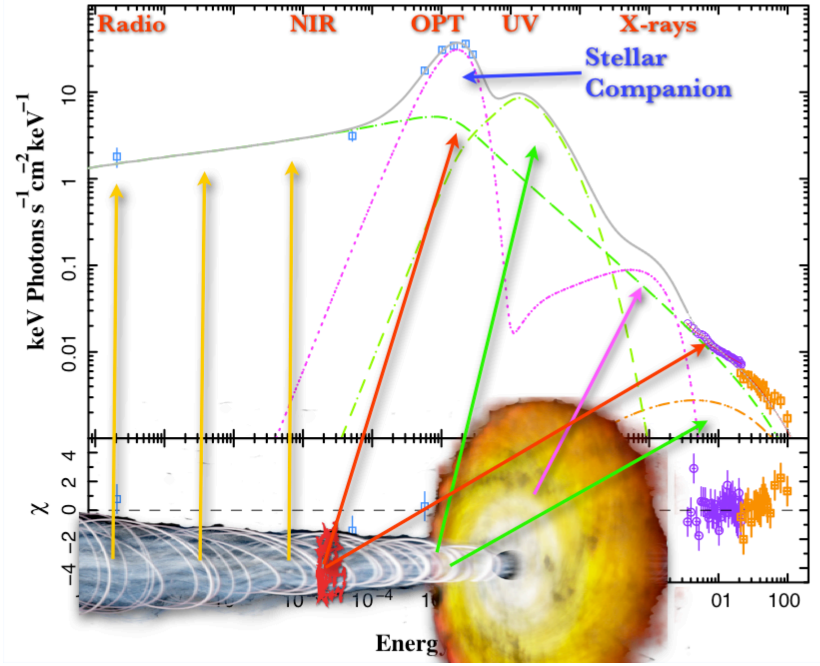
Jet launching

« à la » Blandford & Koenigl (1979)



Credits: M. Coriat

Gandhi et al. (2011)



- The jets can be seen in both the NIR and in radio
- Synergy optical and radio interferometric observations
  - the disk/jet/wind interaction (like in SS 433 and Bp Cru)
  - astrometric shift in the NIR centroid during state transitions

Thanks